# Exploring Possible Dark Matter Models for DAMA and CoGeNT

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0908.2991, 0910.0007

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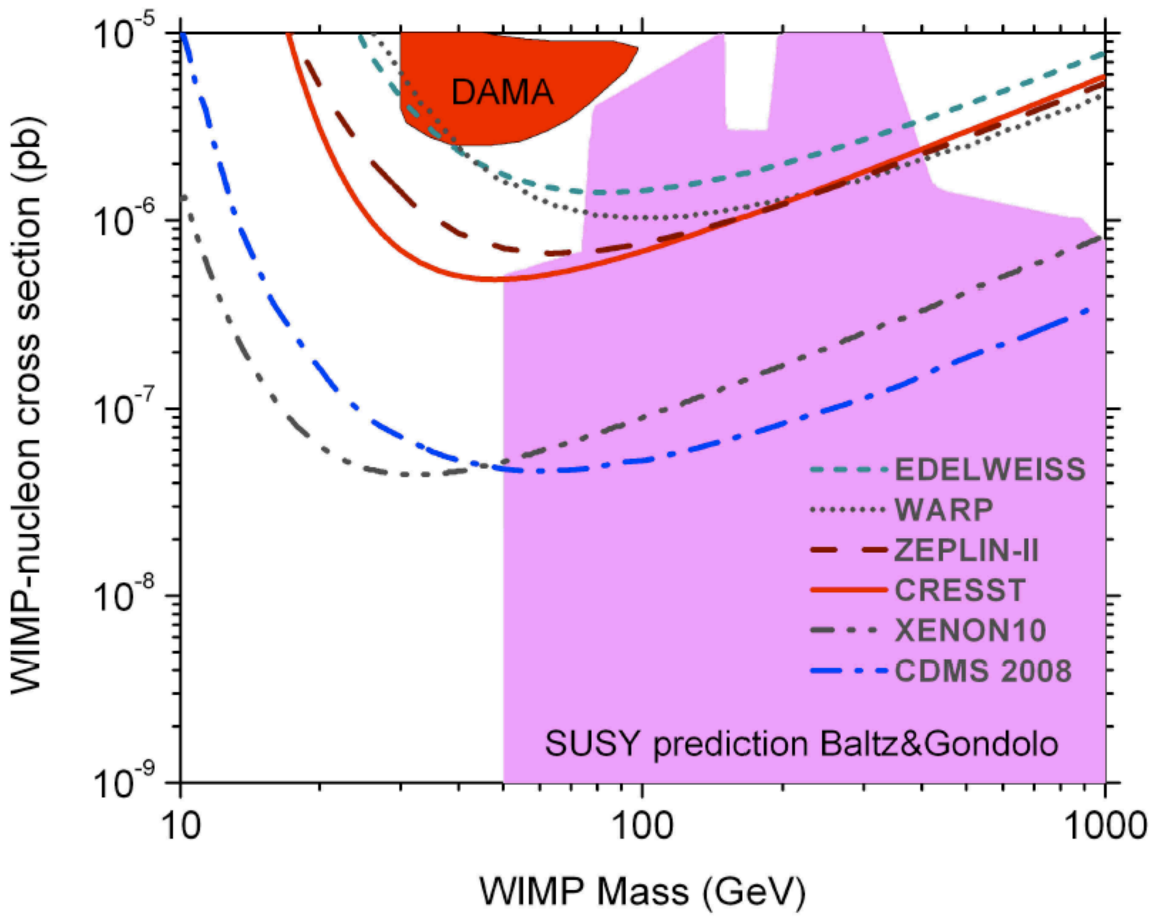
# Outline

- Direct Detection Experiments
- Models with Non-standard Scattering
- DAMA and CoGeNT, and experimental uncertainties
- Dark Moments, and more

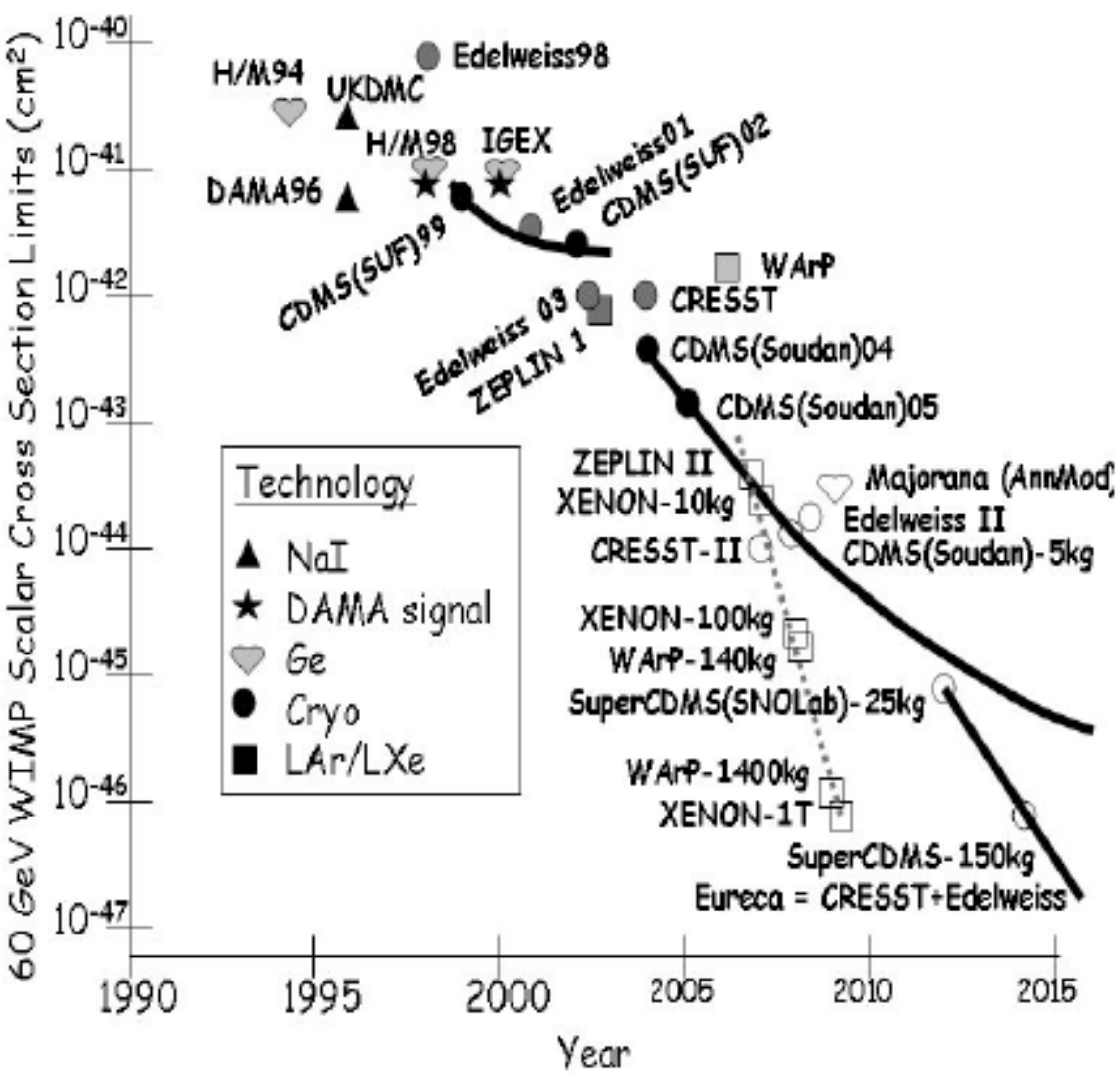
# Direct Detection

- Observe nuclear recoils due to Dark Matter scattering
- Put constraints on cross-section vs. mass
- Lots of experiments: DAMA, CDMS, CRESST, XENON...




arXiv:0809.1892

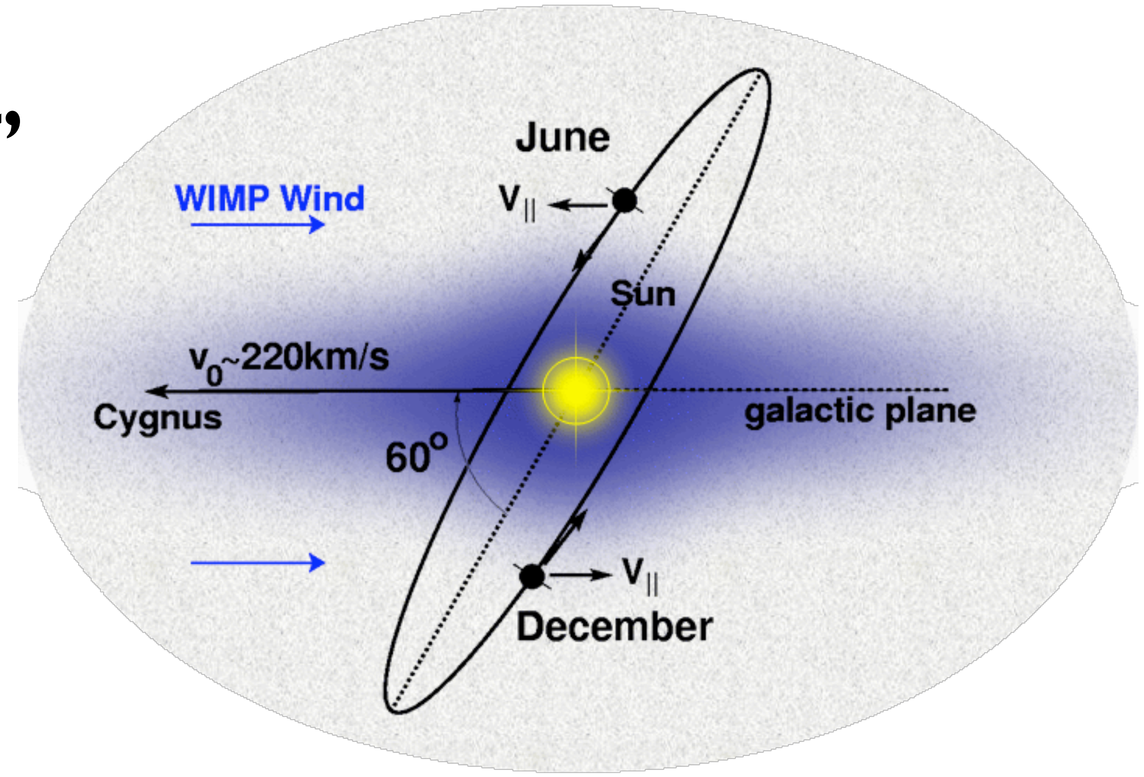
# History of DD Limits

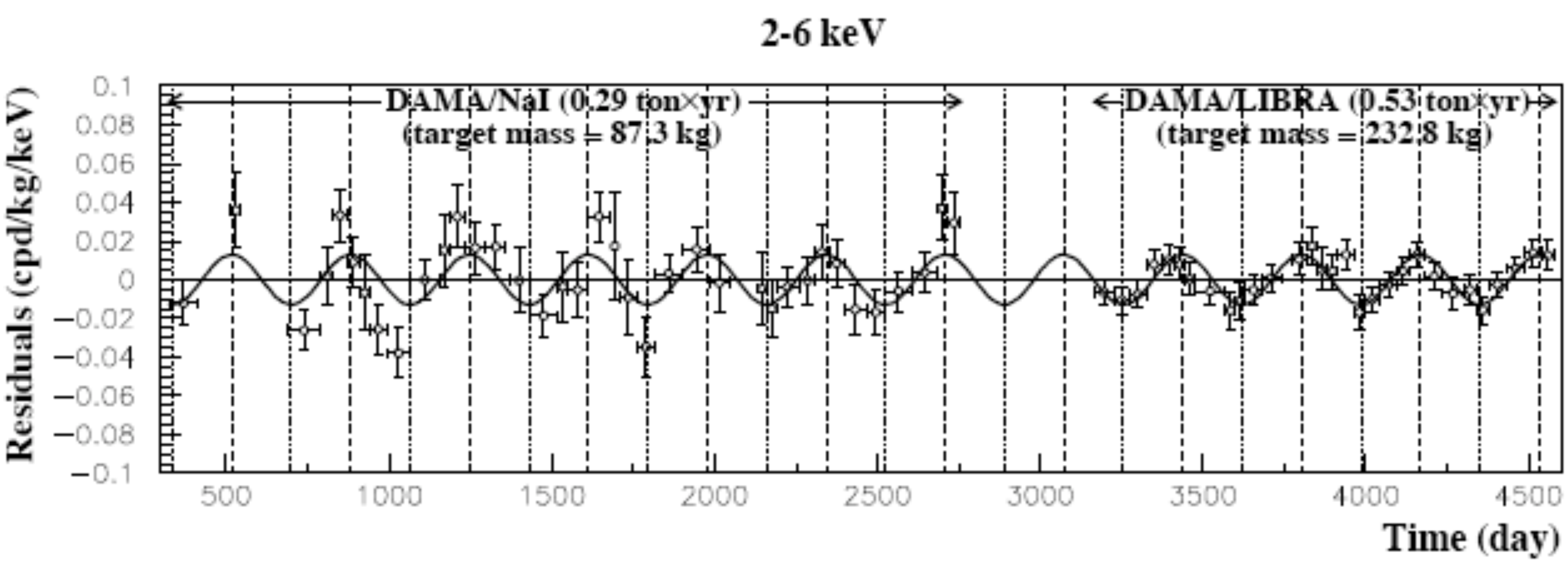



Cushman, 2001

# DAMA annual modulation

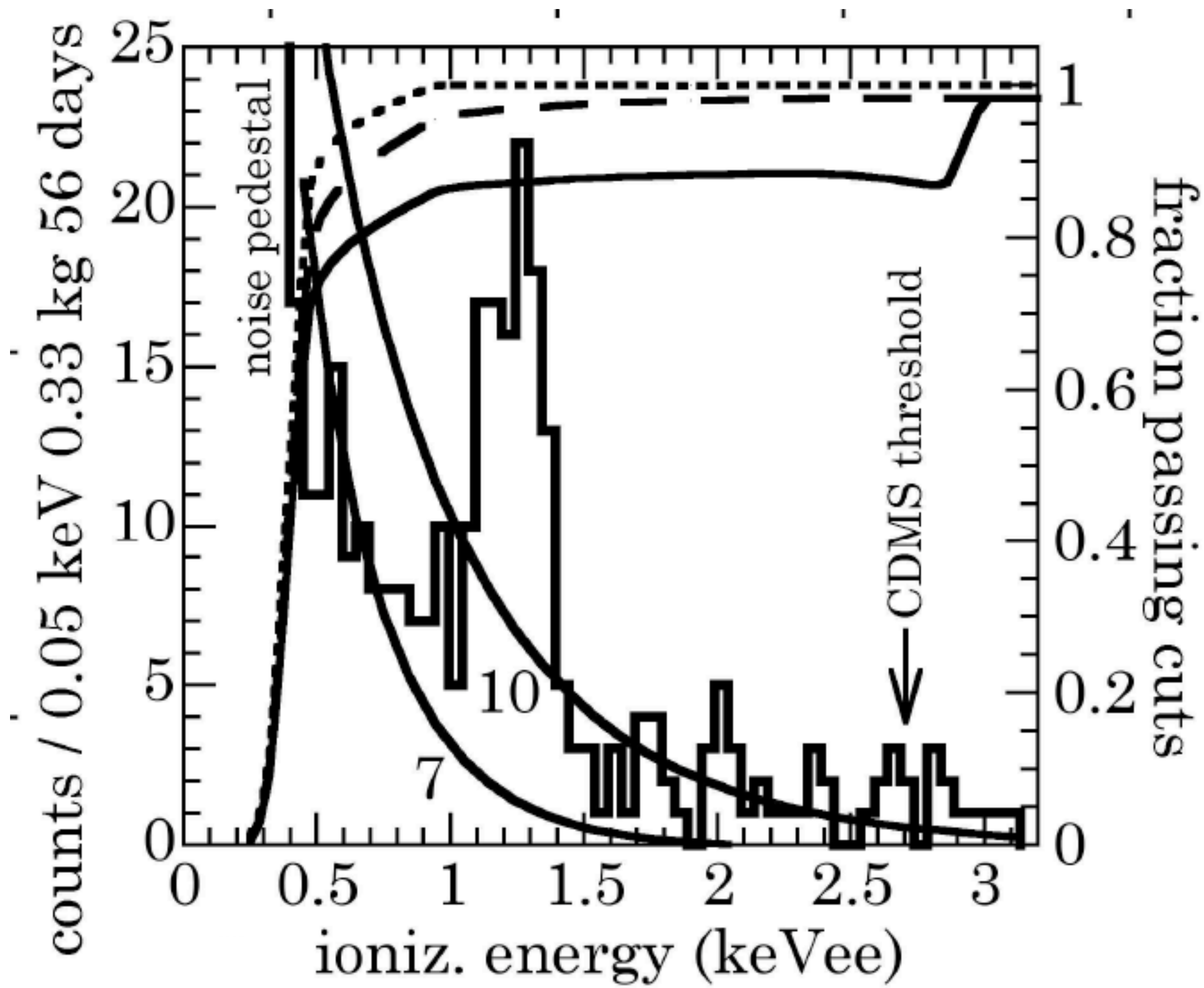
- DAMA sees 8sigma(?) effect, increasingly in phase with earth's motion



- Known backgrounds are much too small: DAMA considered neutrons, muons, neutrinos, temperature...
- Standard WIMP explanation is ruled out by other direct detection experiments

# CoGeNT low-energy signal




Aalseth et al, 2010

# Null Results

- Lots of other experiments w/o discoveries:
- CDMS, XENON, CRESST, SIMPLE, etc.

- Assuming DAMA and/or CoGeNT signals are dark matter, what models are consistent with all data?

# Differences between DAMA and others

- 1) Nuclear mass (DAMA uses NaI, CDMS uses Ge, etc.)
- 2) Different ranges in nuclear recoil energy
- 3) Only experiment to look at annual modulation
- 4) DAMA doesn’t veto purely E&M events
- 5) Crystal Structure
- 6) Spin of nucleus

# Event Rate Formula

- Events per unit time per detector mass per unit recoil energy

local DM density

$$\frac{dR}{dE_R} = N_T \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v_{\rm min}} d^3v f(v) v \frac{d\sigma}{dE_R}$$

Nuclei/detector mass

Kinematic Limit

DM/Nucleus cross-section

DM Halo Distribution

$$v_{\rm min} = \frac{q}{2\mu}$$

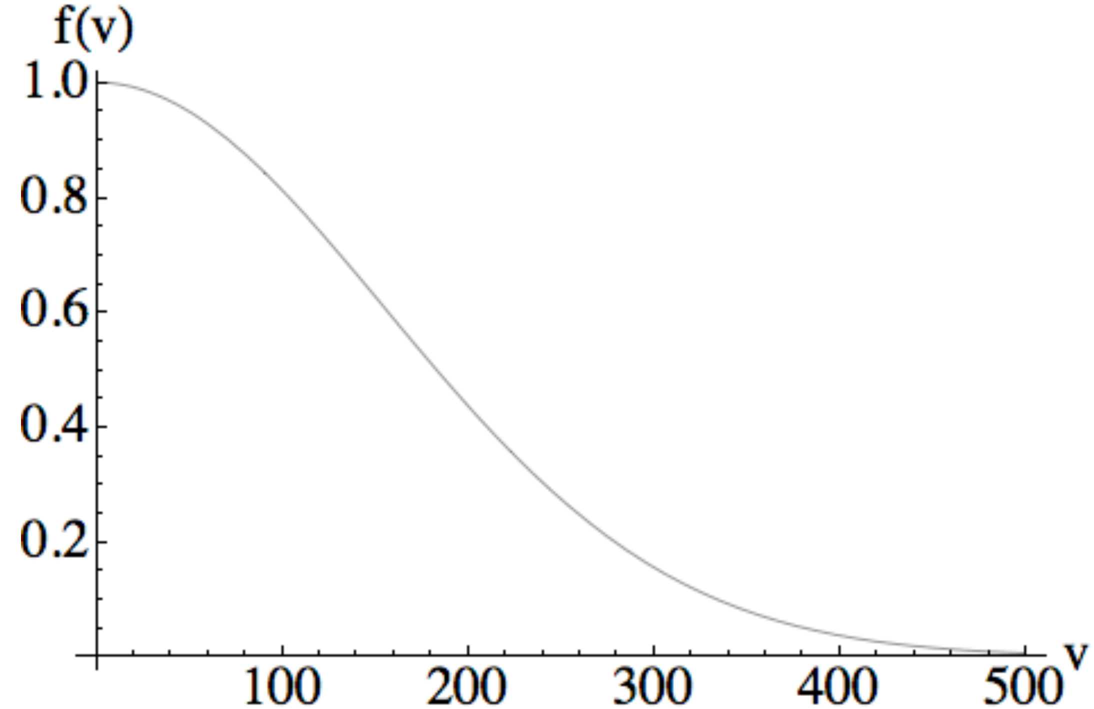
$$f(v) \sim e^{-(v/\bar{v})^2}$$

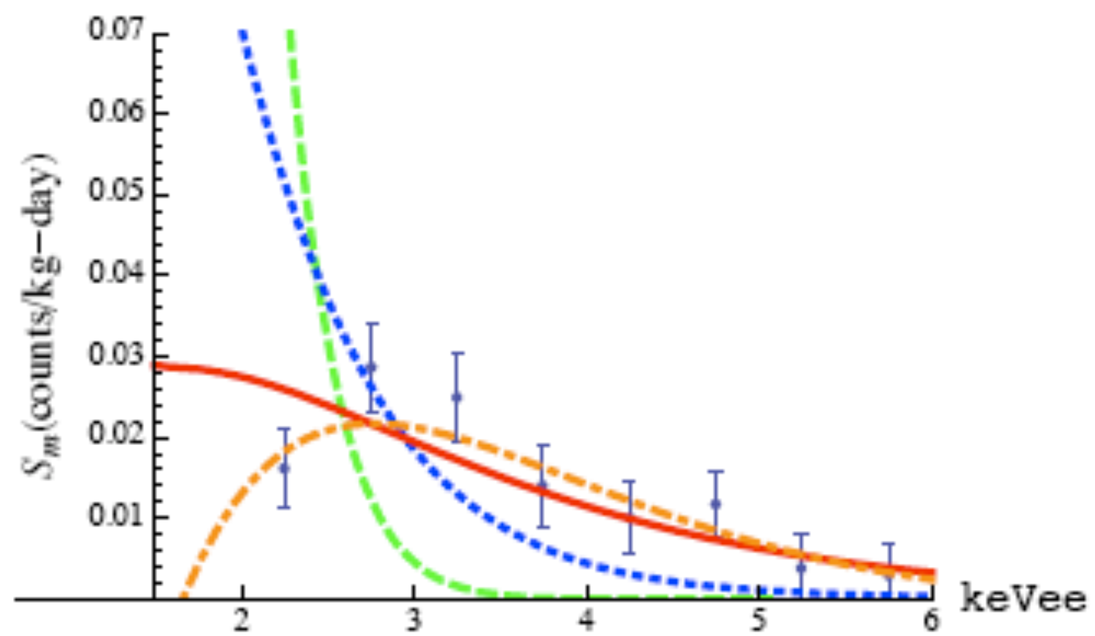
# Enhanced Modulation?

$$v_{\min} = \frac{q}{2\mu}$$

Small mass ➔ larger modulation

But bad spectrum, overprediction at low recoil energy



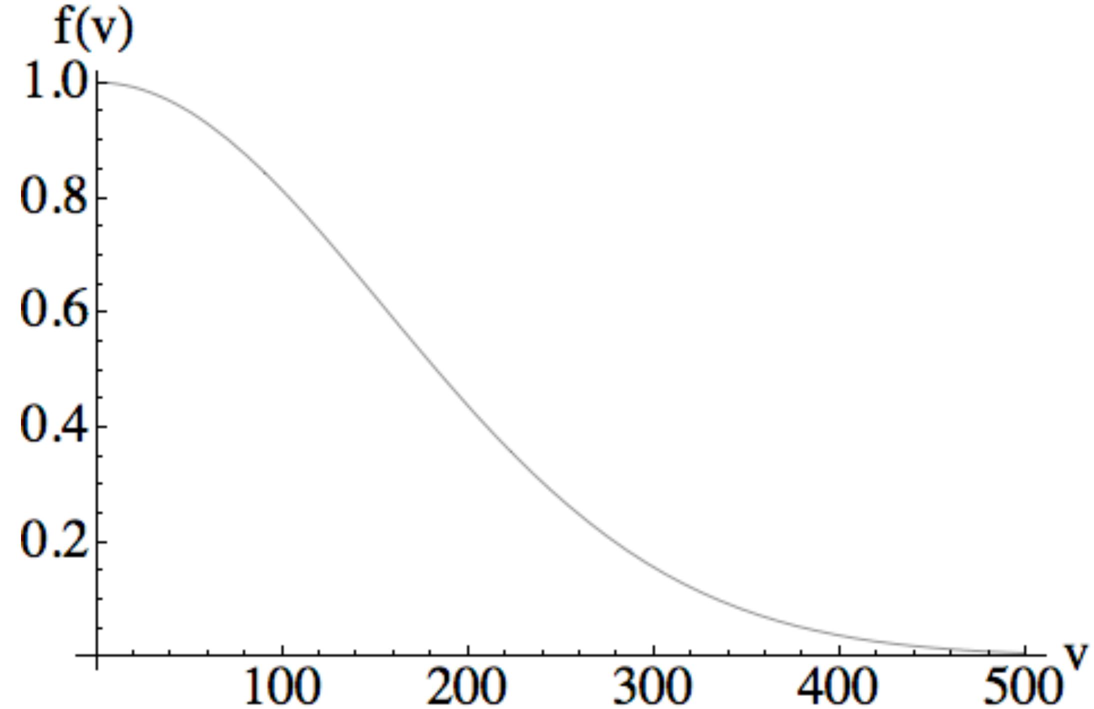




Chang, Pierce, Weiner 0808.0196

# Enhanced Modulation?

Inelastic:

$$v_{\min} = \frac{q}{2\mu} + \frac{\delta}{q}$$




Mass splitting $\rightarrow$ larger modulation

Tucker-Smith, Weiner 2001

# Lots of model ideas

- inelastic scattering
- Light dark matter, Na scattering (issues w/ spectrum...)
- Electronic scattering/signal (especially, "luminous dm")
- Channeling (but, theoretical problems...)
- Spin-dependent (constraints from SIMPLE, etc...)
- Resonant DM
- Form Factor DM/Momentum-dependent DM

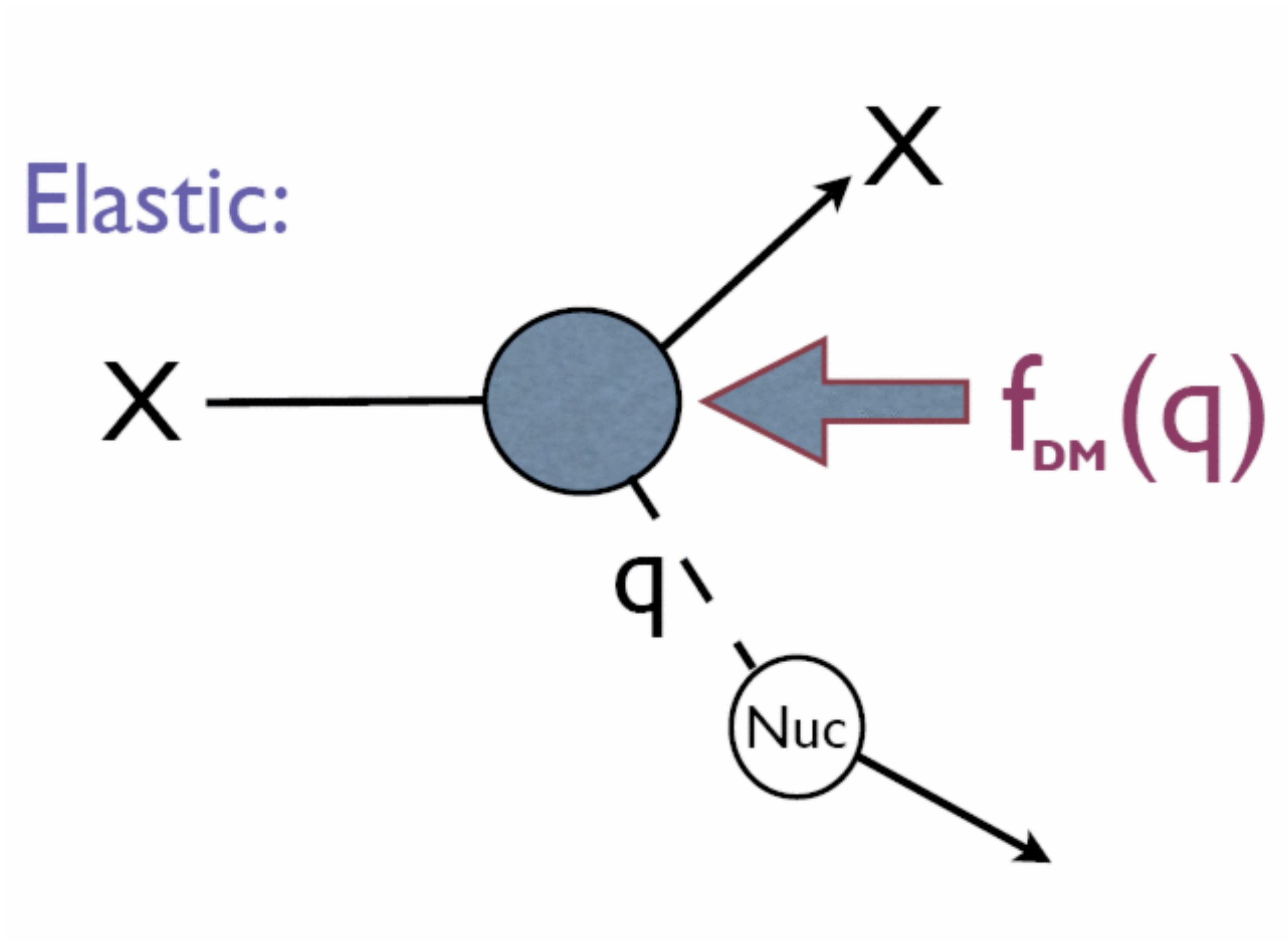
# Form Factor DM

Feldstein, ALF, Katz

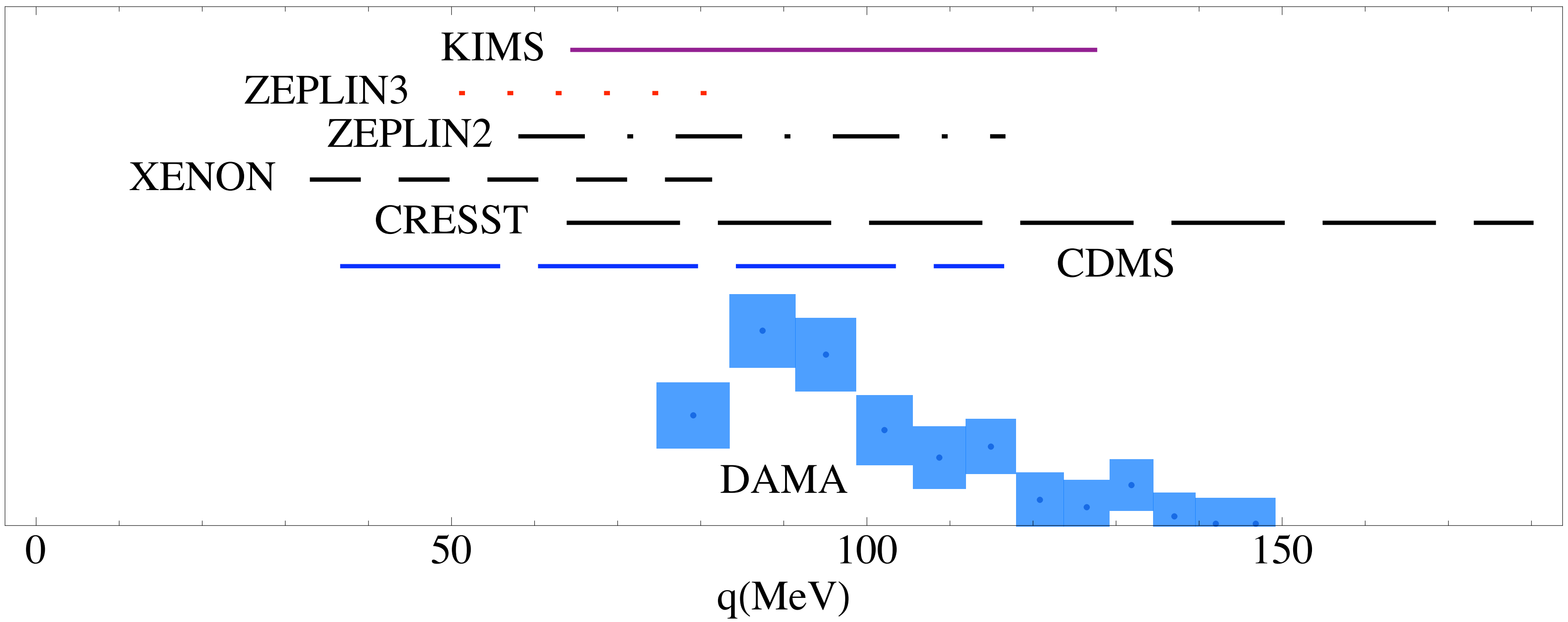
- Introduce form factor in dark matter scattering coming from dark matter internal structure

$$\frac{dR}{dE_R} \to \frac{dR}{dE_R} f_{\rm DM}^2(q)$$

$$q = \sqrt{2m_N E_R}$$

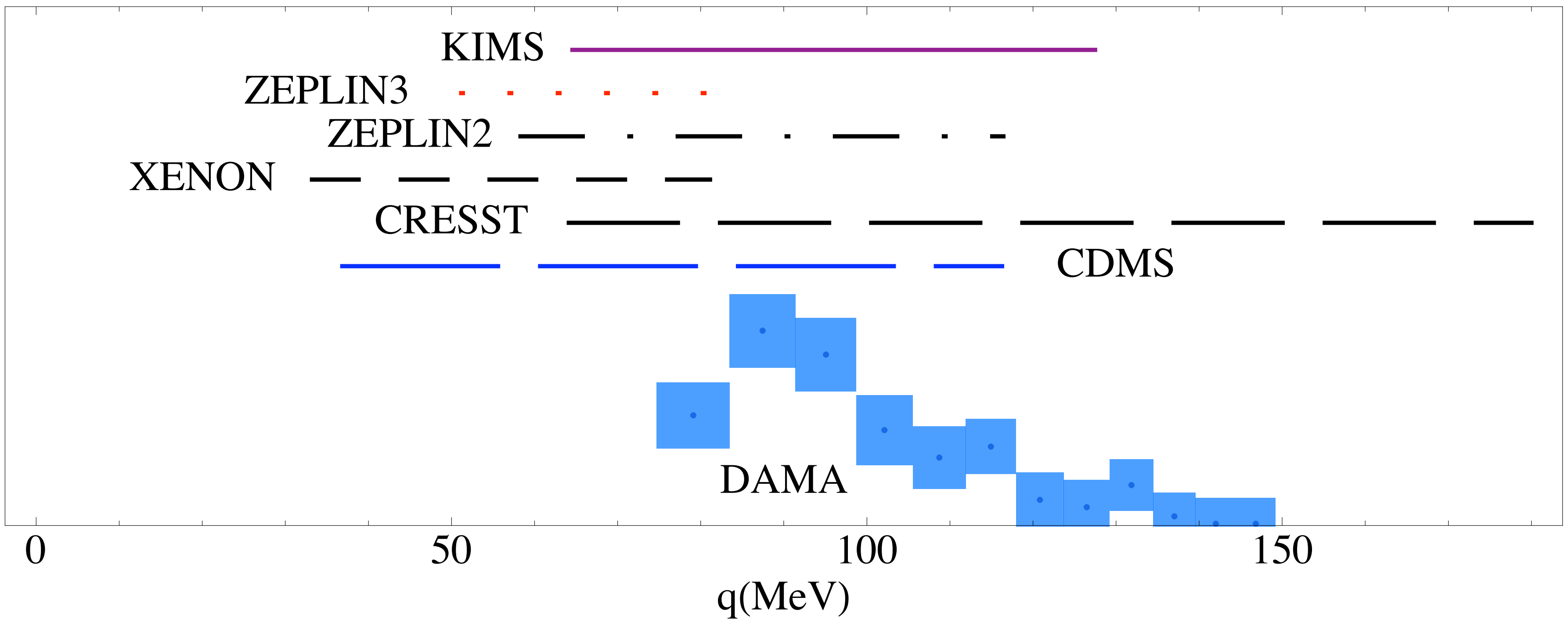


# Overlap in q




- DAMA predicts events between 80 MeV and 120 MeV
- Include f(q) to suppress events below DAMA region

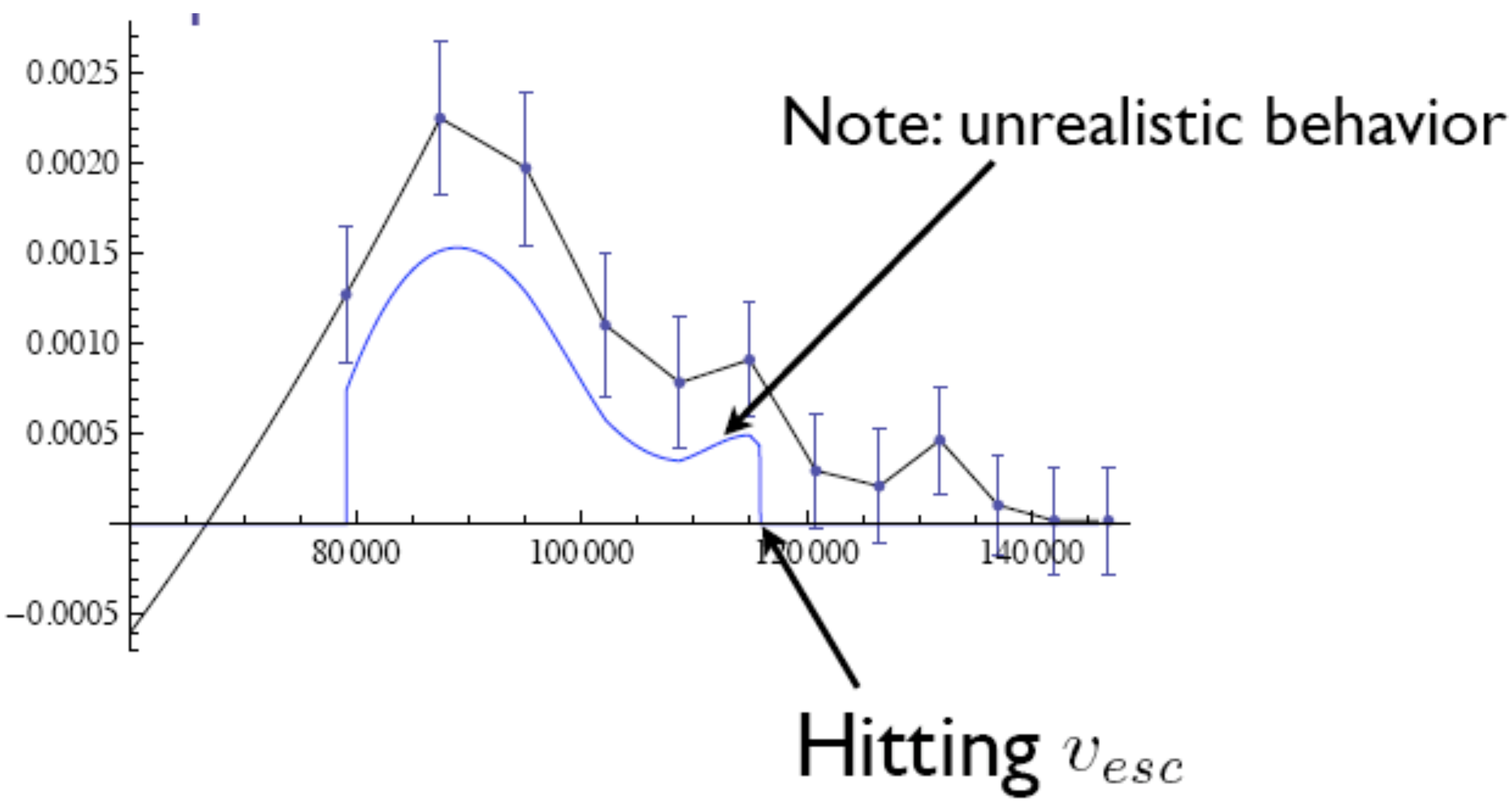
# Overlap in q




- Simple example: $\mathcal{L} \supset \partial_\mu X \partial_\nu X^* F^{\mu\nu}$ $\quad f_{\rm DM}(q) \propto q^2$
- More general f(q) needs more complicated model

# Minimum CDMS prediction

Idealized Form Factor

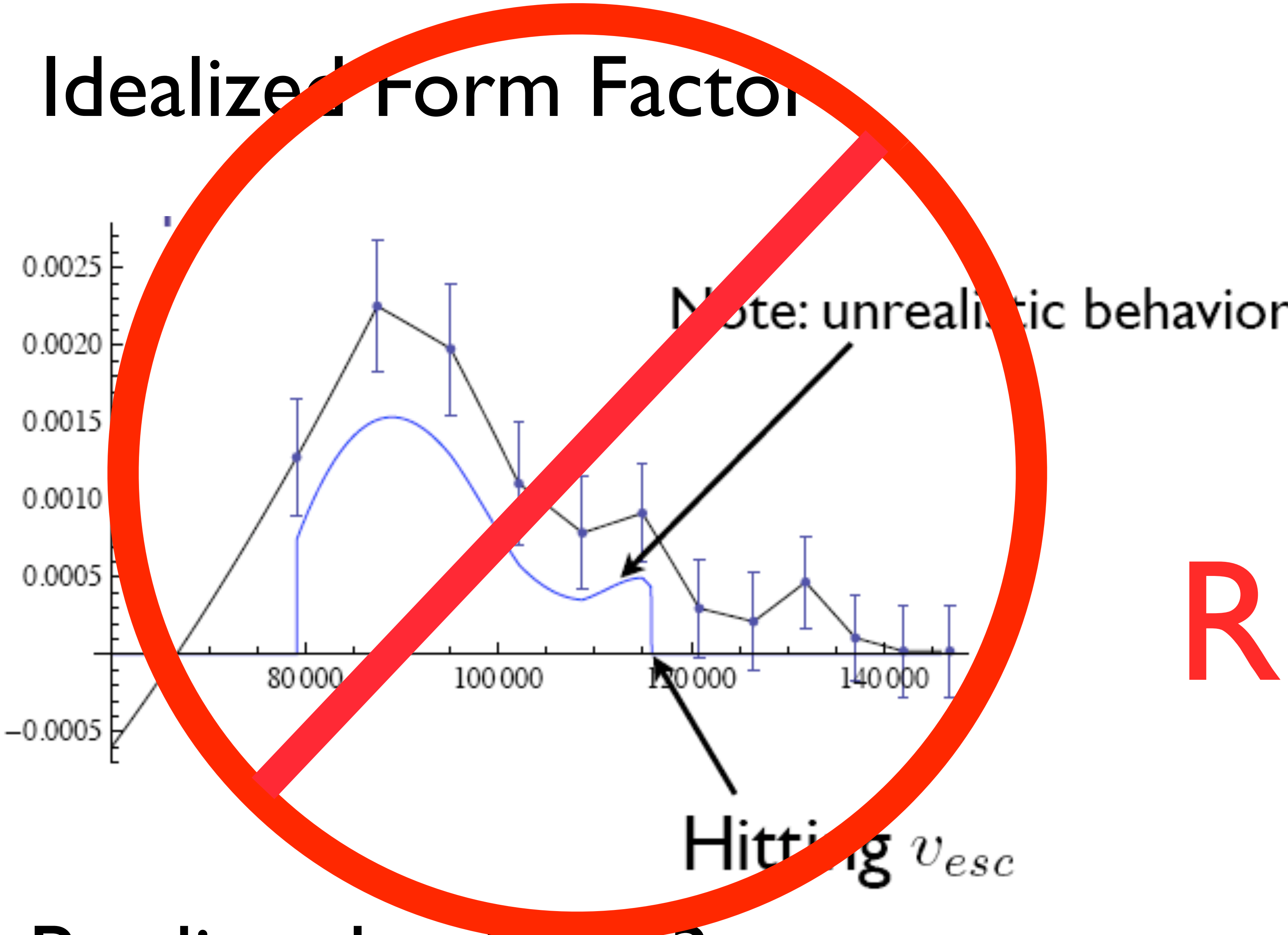



Predicted at least 3 events at CDMS between 40 - 60 keV

CDMS saw 0

# Minimum CDMS prediction

Idealized Form Factor




Ruled Out!

Predicted at least 3 events at CDMS between 40 - 60 keV

CDMS saw 0

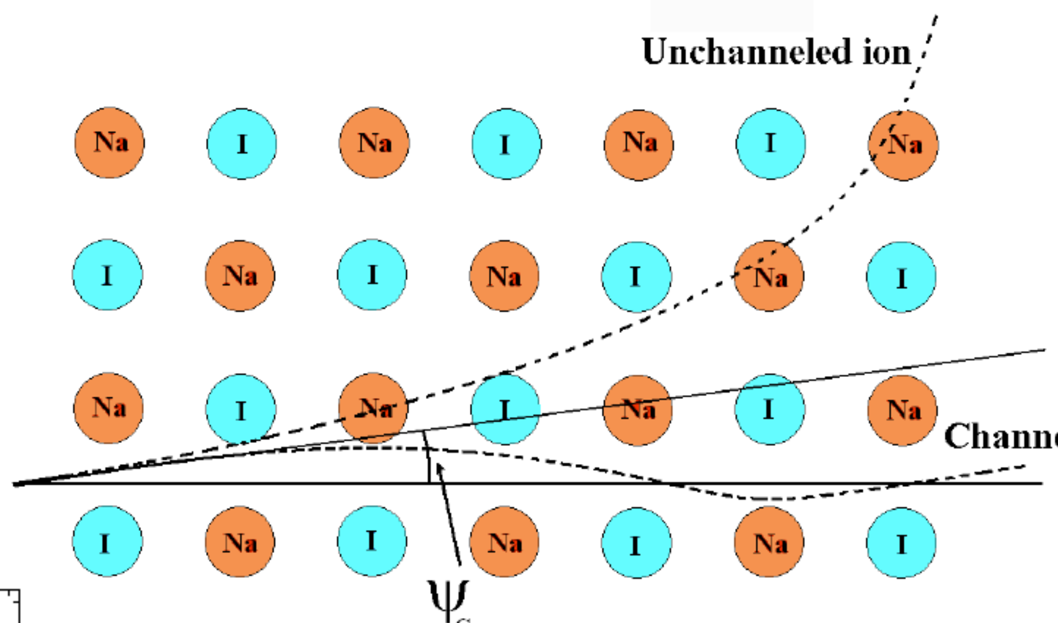
# Quenching factors

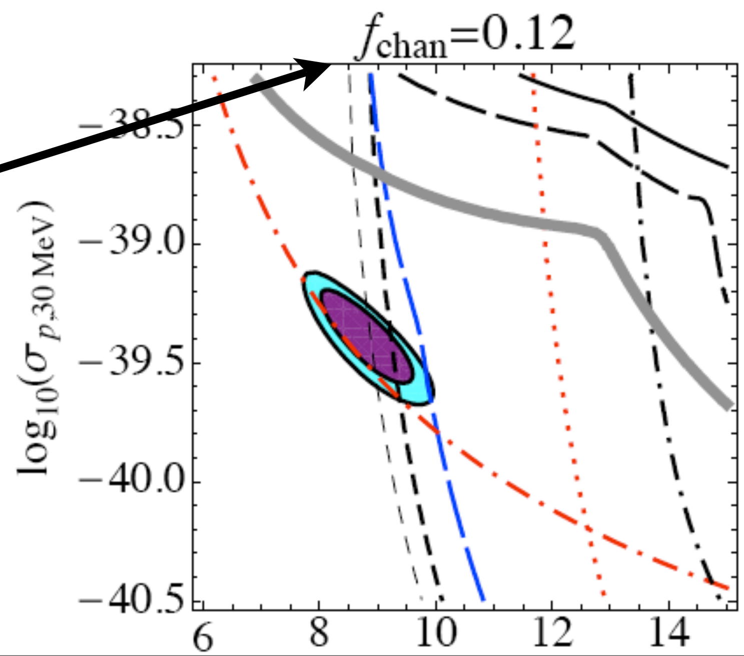
- Nuclear recoils usually lose only ~ fractions of their energy electronically, most energy is lost to nuclear collisions ➔ heat.
- Fraction is called a "quenching" factor q, = 9% for iodine at DAMA
- Not measured directly at all relevant energies, and uncertainties can be important!
- Some events at very low DAMA energies have very different quenching factor, due to crystal structure. Example: Channeling

# Channeling

Lindhard, Drobyshevski

- Quenching factor would be much closer to one some fraction of time at low energies
- Then a 20 keV event at DAMA would really be a 2 keV event
- At light DM masses, DAMA would be sensitive, but most other experiments wouldn't




Channeling fraction here chosen as small as possible

$f_{\rm DM}(q) \propto q^2$ would be consistent

Feldstein, ALF, Katz, Tweedie

# Channeling

- Theoretically disfavored
  - Bozorgnia, Gelmini, Gondolo

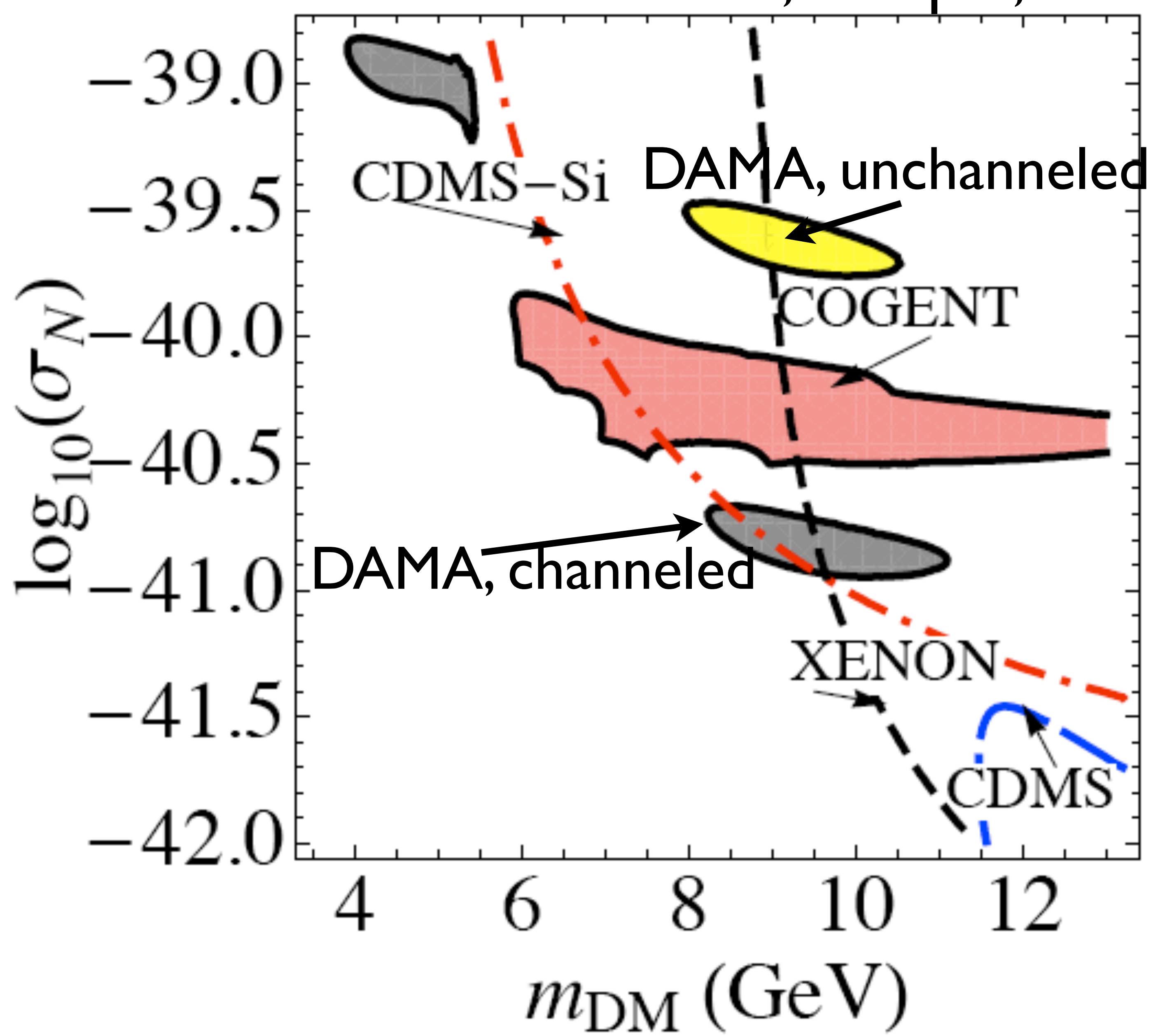
  Discuss it anyway for
- 1) Historical (~ 6 mo.) context
- 2) More general issue - quenching factors are not known at very low energies. A more detailed theoretical study would be valuable...

# CoGeNT ~ DAMA?

DAMA and CoGeNT regions are very similar.

Still, can we do better?

ALF, Hooper, Zurek




Hooper et al (2010): How well do we know Sodium scattering region?

World average is $q_{\mathrm{Na}} \sim 0.3 \pm 0.01$ , but is this reliable?

# Na Low-E Quenching factor

Gerbier et al

Astroparticle Physics 11 (1999) 287–302

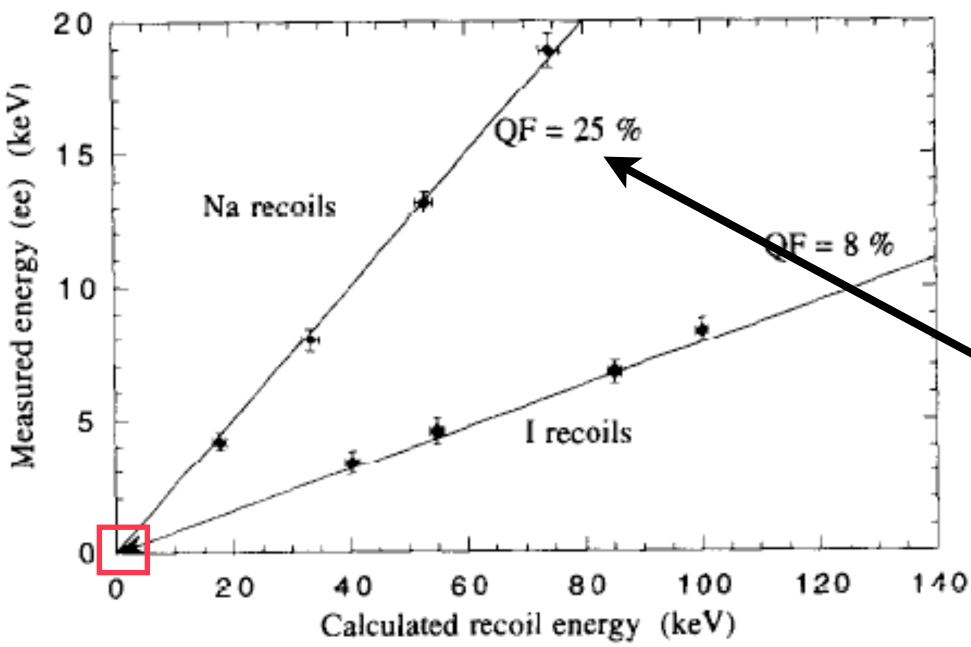



Fig. 2. Measured recoil energy in NaI(Tl) as a function of the real kinetic energy of the recoils on Na and I nuclei.

Fit q as a constant over large energy range

Barnabei et al

Physics Letters B 389 (1996) 757–766

Relevant region

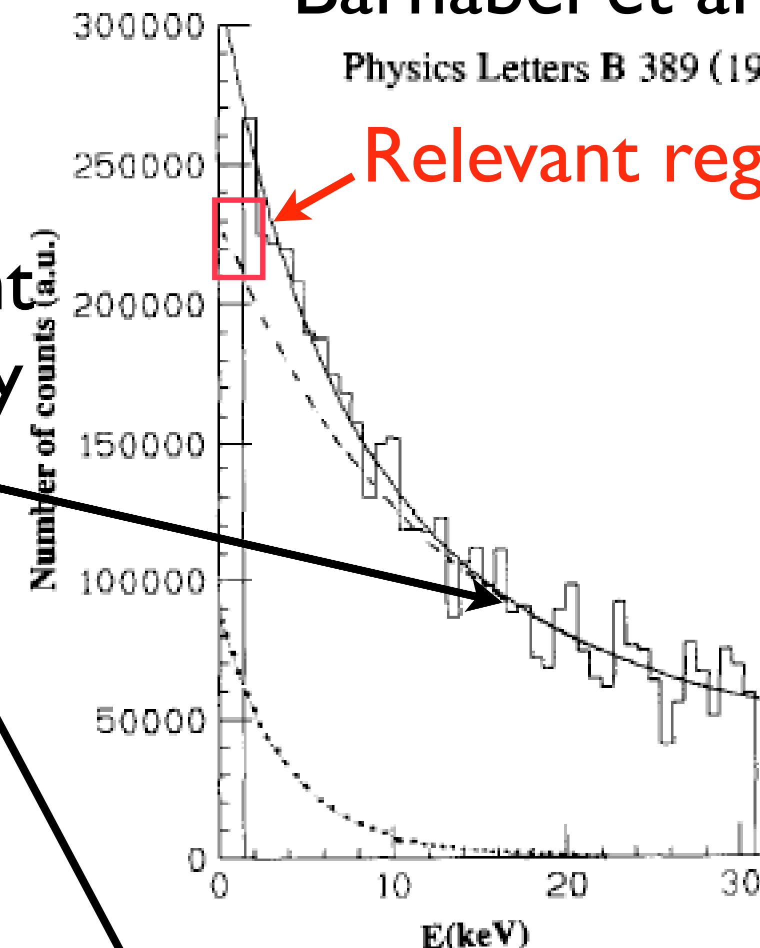


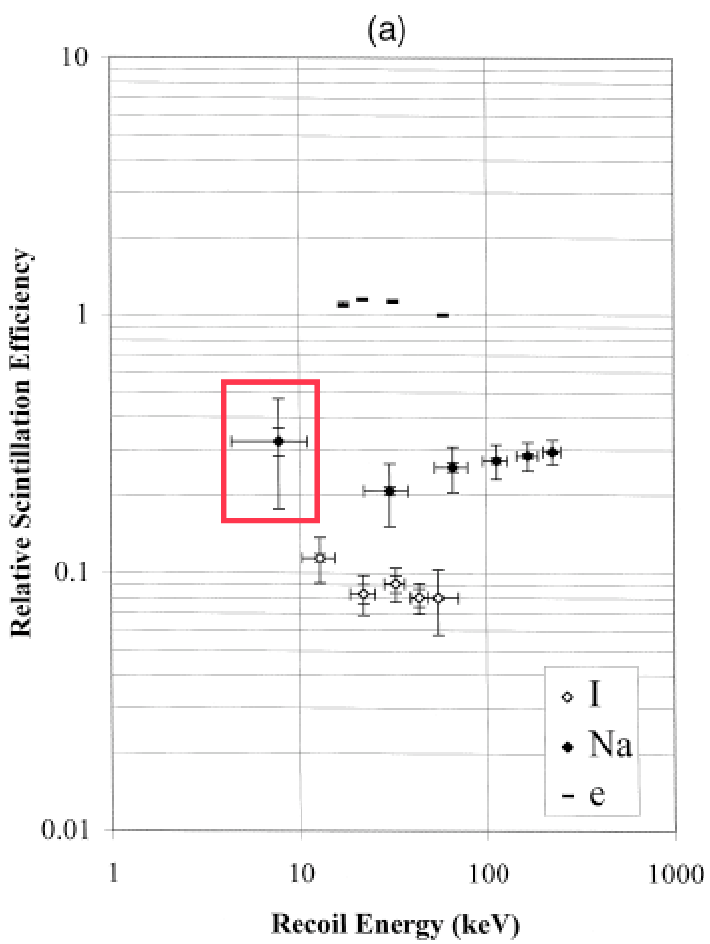

Fig. 1. Experimental low-energy spectrum only due to neutron elastic scattering; the continuous line represents the fitted curve ($\chi^2/(39\,\mathrm{d.o.f.}) = 1.3$). The dotted and dashed lines indicate the component of $^{127}$I and $^{23}$Na, respectively.

$$Y(E_{\mathrm{det}}) = \alpha_{\mathrm{Na}} G_{\mathrm{Na}}\left(\frac{E_{\mathrm{det}}}{q_{\mathrm{Na}}}\right) + \alpha_{\mathrm{I}} G_{\mathrm{I}}\left(\frac{E_{\mathrm{det}}}{q_{\mathrm{I}}}\right)$$

$$G_X(E_R) = \exp(a_{1,X} E_R^3 + a_{2,X} E_R^2 + a_{3,X} E_R)$$

Tovey et al

Physics Letters B 433 (1998) 150–155




But not very sensitive at low energies!

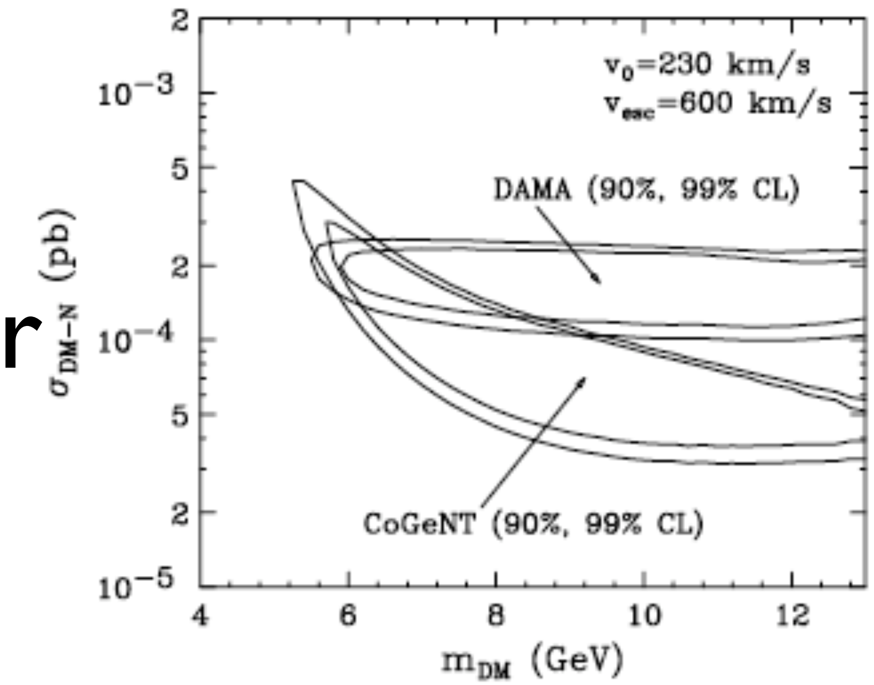
Fushimi et al

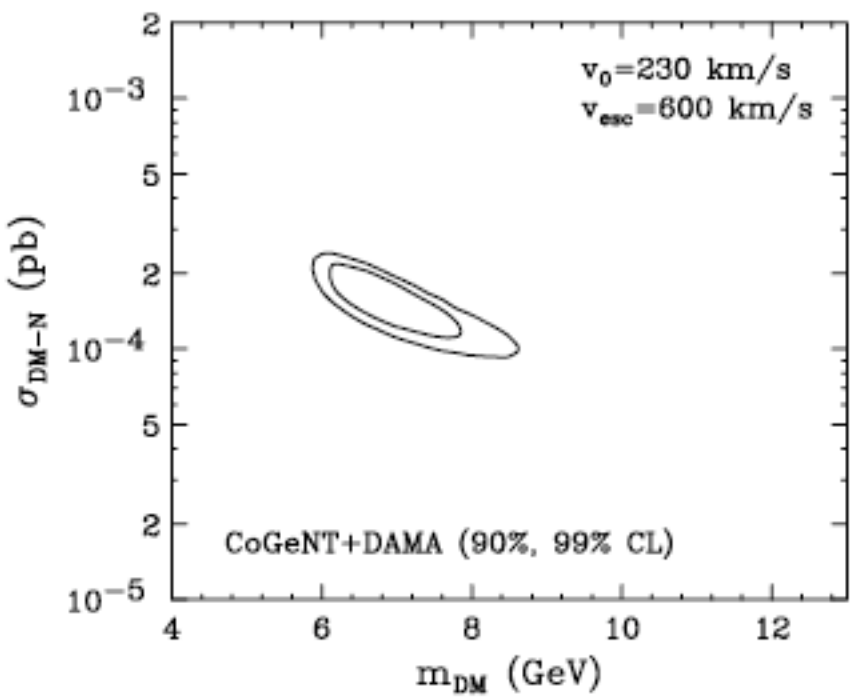
PHYSICAL REVIEW C 1993
VOLUME 47, NUMBER 2

$f_{\mathrm{Na}} = 0.4 \pm 0.2$

# Sodium scattering revisited

~ 7 GeV
Dark Matter

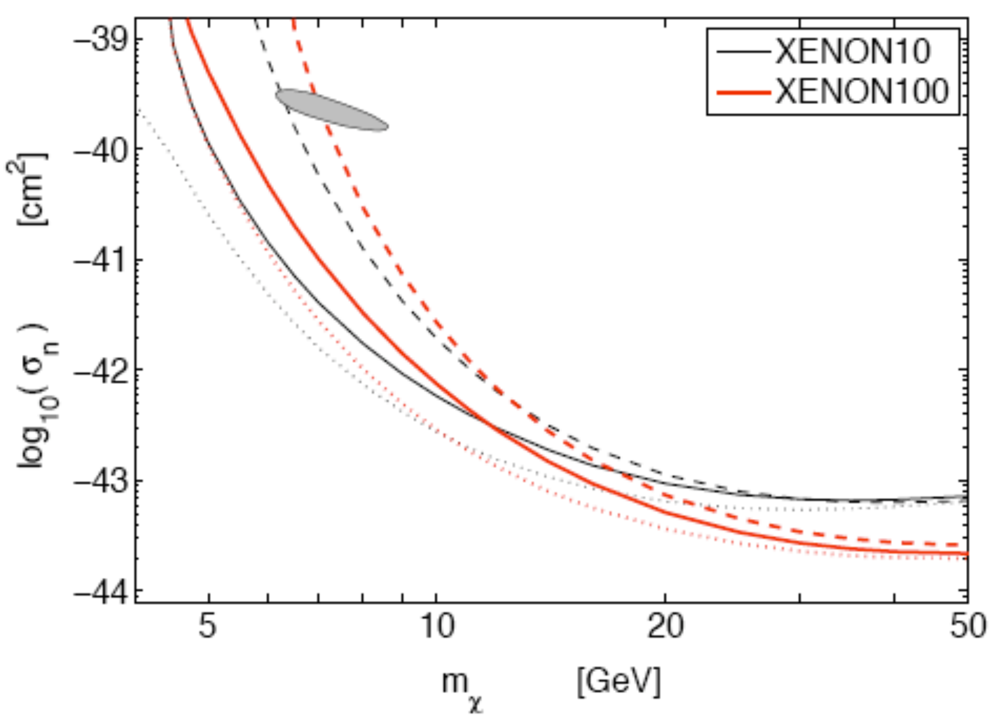



Hooper et al 2010

Still, some tension
with XENON10

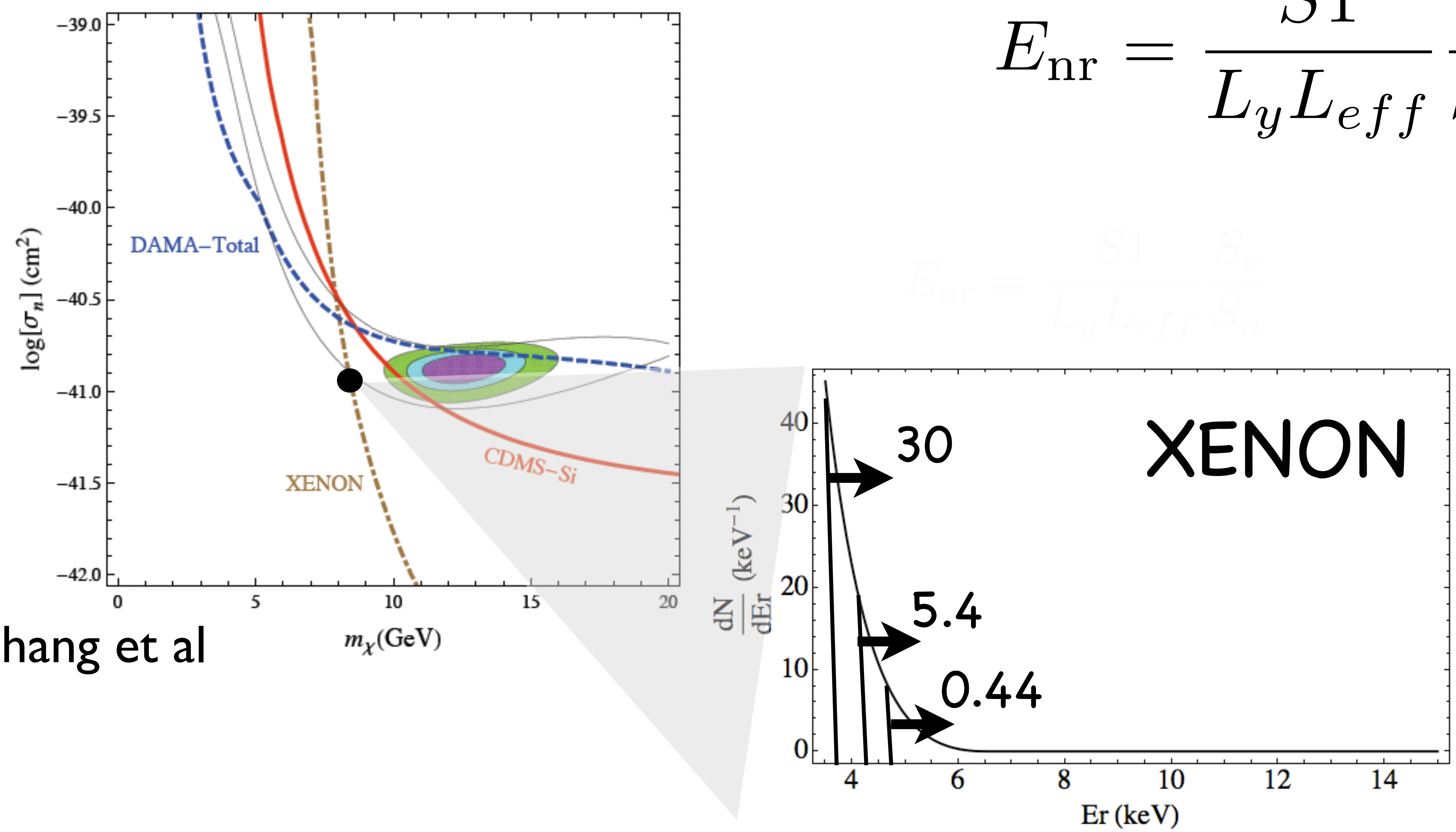
Sorensen



# XENON Leff

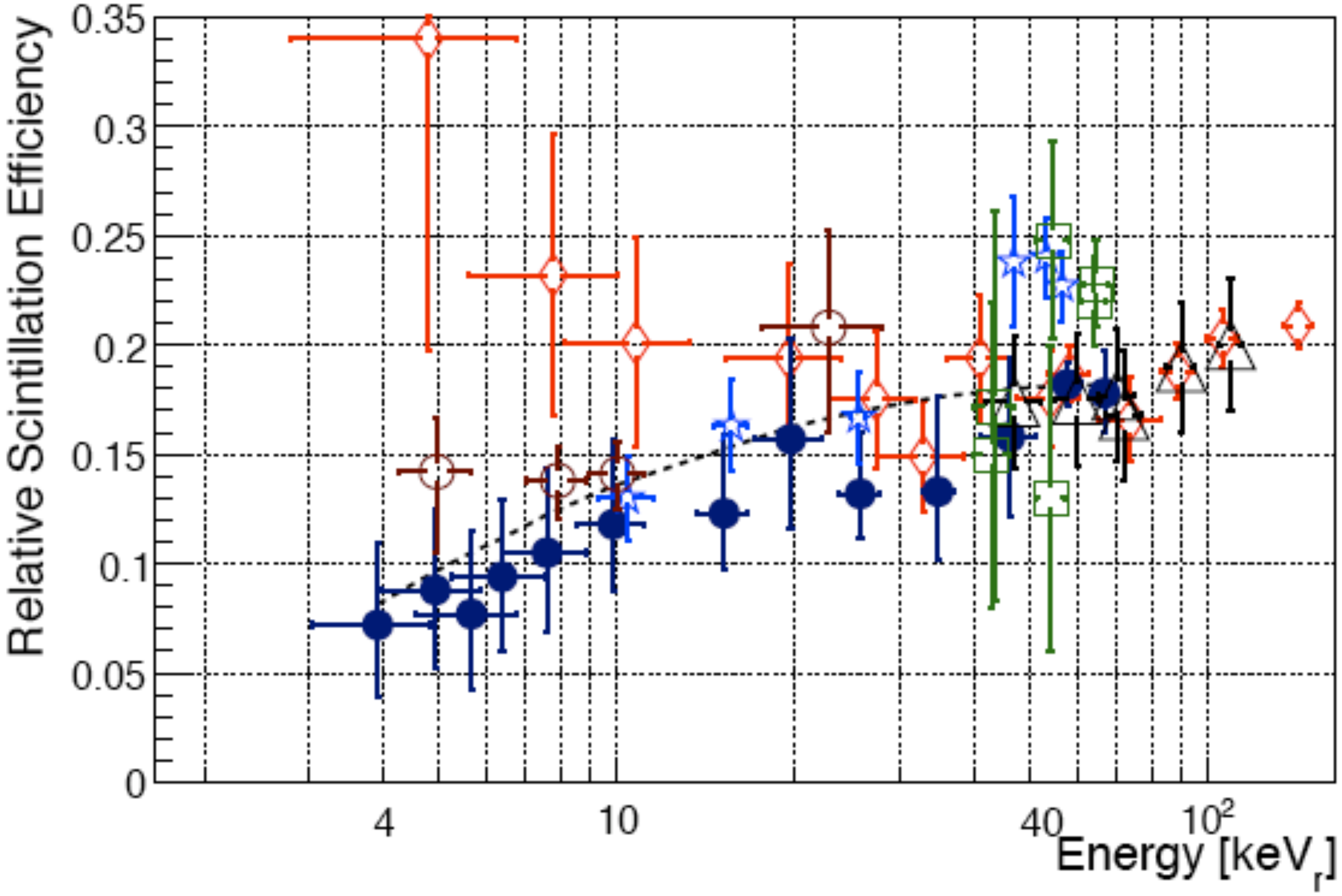
- Constraints are extremely sensitive to what the exact low-energy threshold is

$$E_{\rm nr} = \frac{S1}{L_y L_{eff}} \frac{S_e}{S_n}$$




-Chang et al

# XENON Leff




$$E_{\rm nr} = \frac{S1}{L_y L_{eff}} \frac{S_e}{S_n}$$

# More Kinematics

- Momentum transfer

$$q = \sqrt{2m_N E_R}$$

Relative velocity

$$v^2(1-\cos\theta) = \frac{q^2}{2\mu^2}$$

$$\hat{v}_i \cdot \hat{v}_f \equiv \cos\theta$$

Reduced DM-Nucleus mass

- q smaller at CoGeNT than DAMA (Sodium)
- $\mu$ larger at CoGeNT than DAMA (Sodium)
- Typical $v$ larger at DAMA than CoGeNT
- Try additional velocity dependence to DAMA & CoGeNT regions closer

# Dark Moments

ALF, Zurek

- Add new massive dark force $A_\mu$ kinetically mixing with photon $\epsilon F_{\mu\nu} B^{\mu\nu}$
- Give dark matter a dark moment interaction

Anapole: $$\mathcal{O}_a \;=\; \bar{\chi}\gamma^\mu\gamma_5\chi A_\mu$$

Magnetic dipole: $$\mathcal{O}_d \;=\; \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}/\Lambda,$$

Dine, Pospelov, Mohapatra, etc.

Anapole: $$\sigma_N = \frac{\mu_N^2}{4\pi M^4}\left(4v^2Z^2F(E_R)^2 - q^2\left(\frac{(m_\chi+m_N)^2}{m_\chi^2 m_N^2}Z^2F(E_R)^2 - 2A^2\frac{J+1}{3J}\frac{b_N^2}{m_N^2 b_n^2}\right)\right)$$

Magnetic dipole: $$\sigma_N = \frac{4\mu_N^2}{\pi M^4\Lambda^2}\left(4q^2v^2Z^2F(E_R)^2 - q^4\left(\left(\frac{2}{m_N m_\chi}+\frac{1}{m_N^2}\right)Z^2F(E_R)^2 - 2A^2\frac{J+1}{3J}\frac{b_N^2}{m_N^2 b_n^2}\right)\right)$$

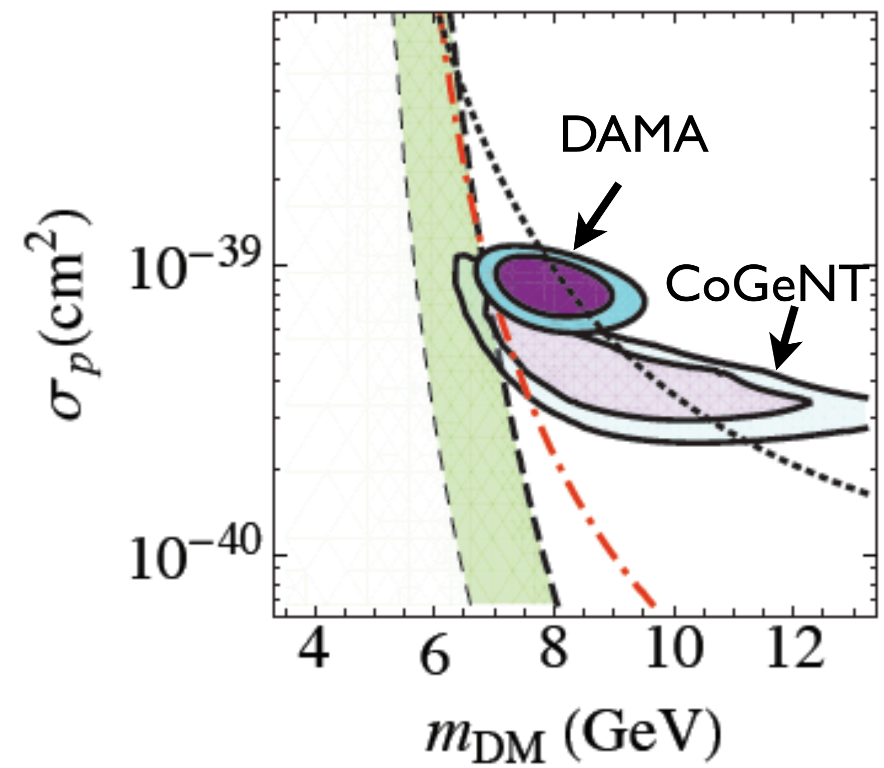
Nucleus spin J

Nuclear magnetic moment $b_N$

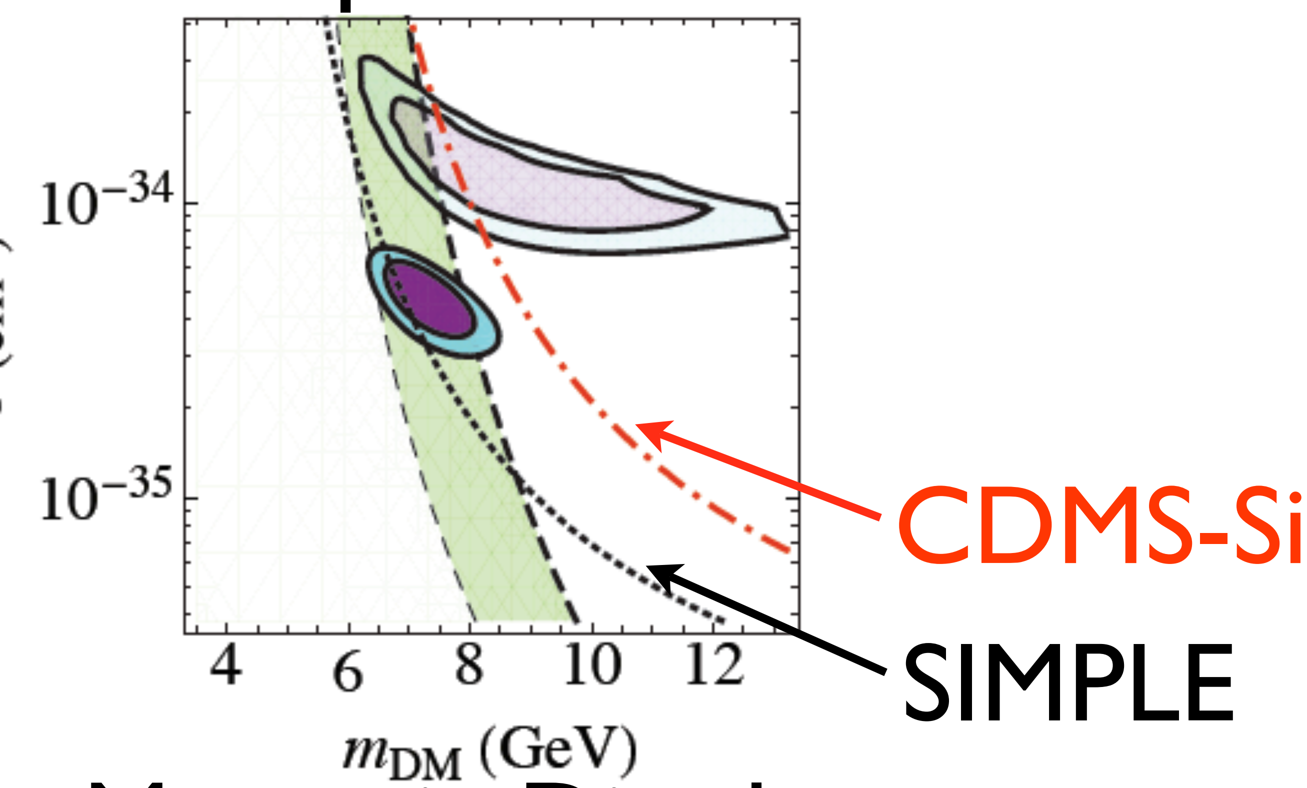
Bohr magneton $b_n$

# Advantages of Dark Moments

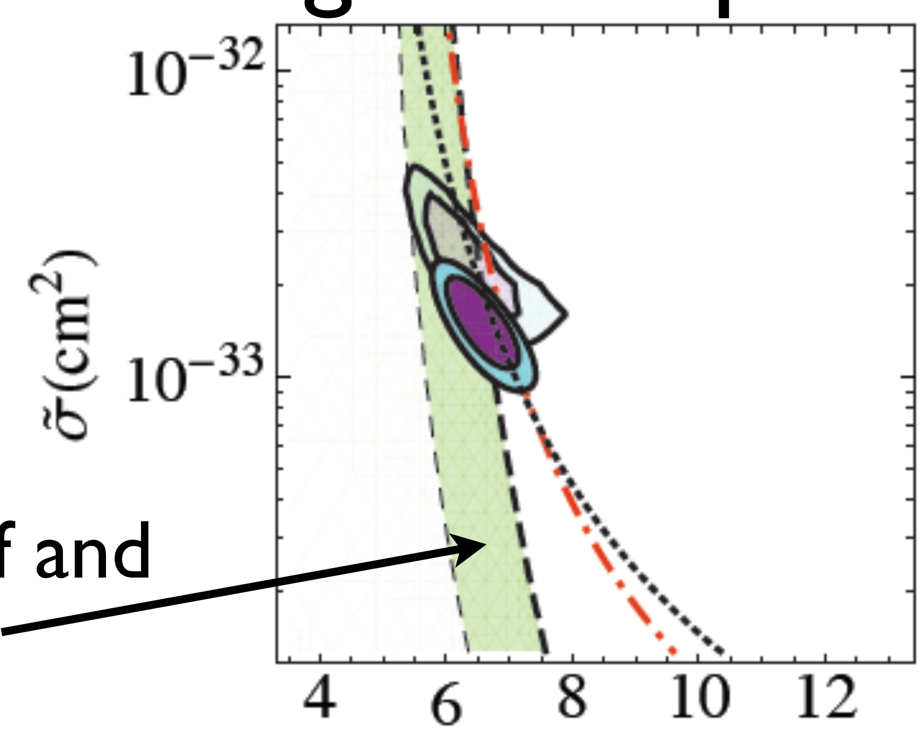
## Standard




## Anapole




## Magnetic Dipole




$$q_{\mathrm{Na}} = 0.45$$

$$v_0 = 270\mathrm{km/s}$$

XENON (depends on Leff and detector resolution)

ALF, Zurek

# Models

- Dark Anapole Example:

  Weyl Fermion: $\chi$ , Dark charge +1

  Scalar: $\phi$ , Dark charge -2

$$\mathcal{L} \supset \bar{\chi}\sigma^{\mu} D_{\mu}\chi + |D_{\mu}\phi|^2 + V(|\phi|^2) + \lambda\phi\chi\chi + h.c.$$

$$\langle\phi\rangle \sim 10\mathrm{GeV}$$

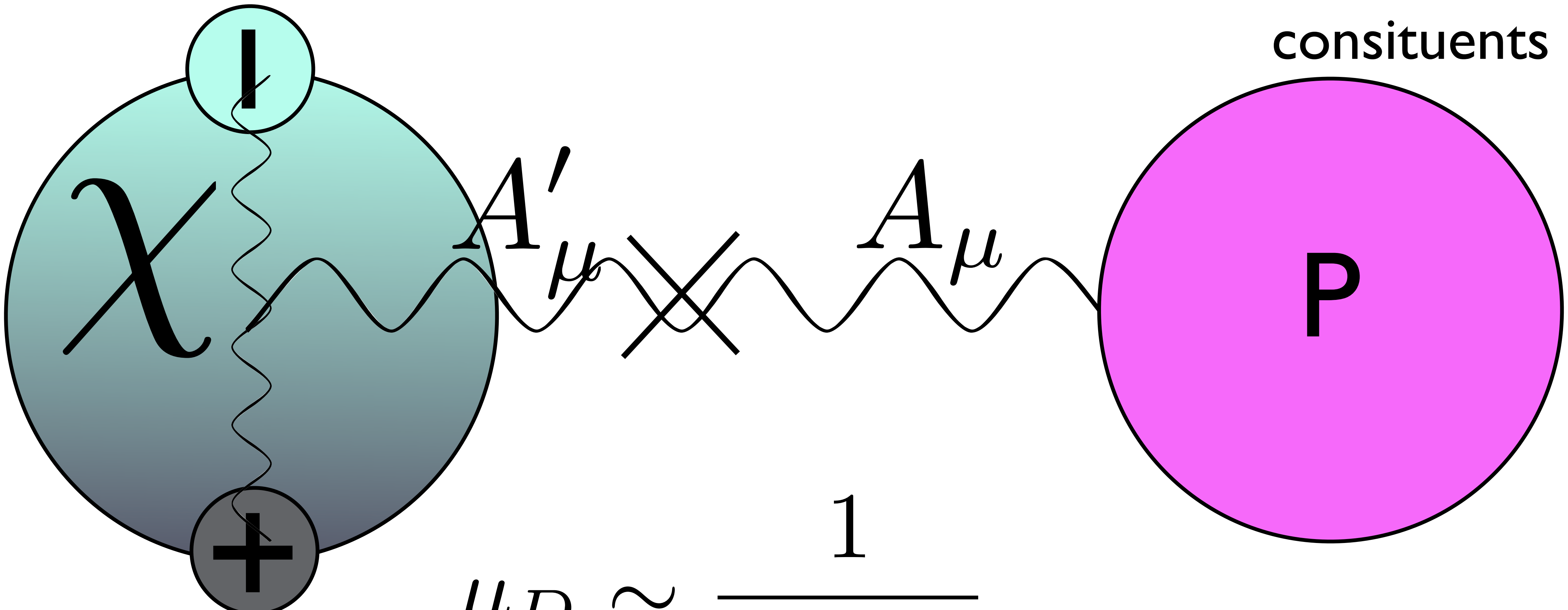
- Generates anapole $\bar{\chi}\gamma^5\gamma^{\mu}\chi\bar{N}\gamma_{\mu}N$
- Now, $\chi$ is Majorana, so standard SI interaction vanishes

$$\bar{\chi}\gamma^{\mu}\chi\bar{N}\gamma_{\mu}N$$

# Models

- Dark Magnetic Dipole Example:

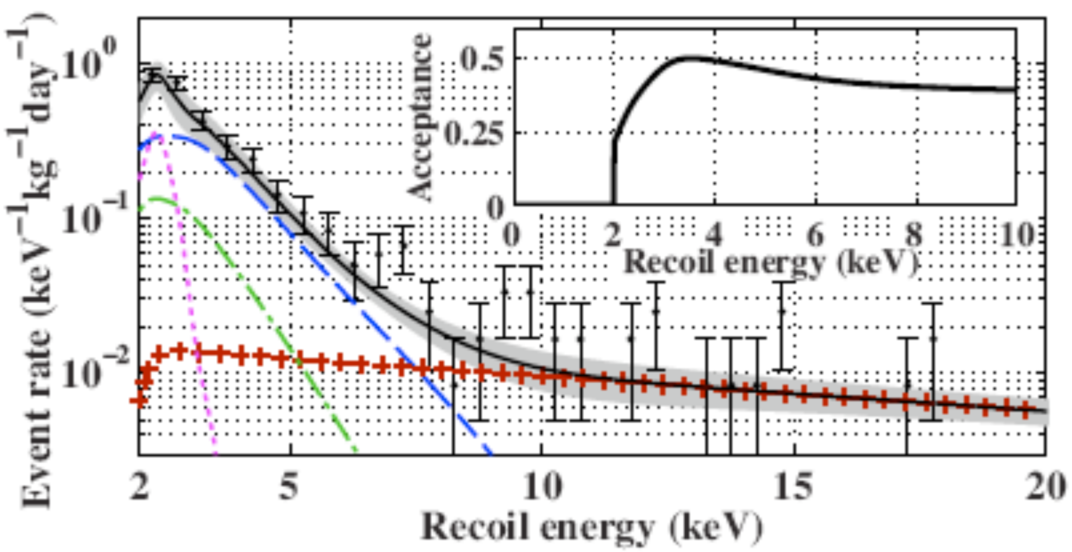
Fairly easy: make DM a composite, neutral under dark force, but with charged consituents

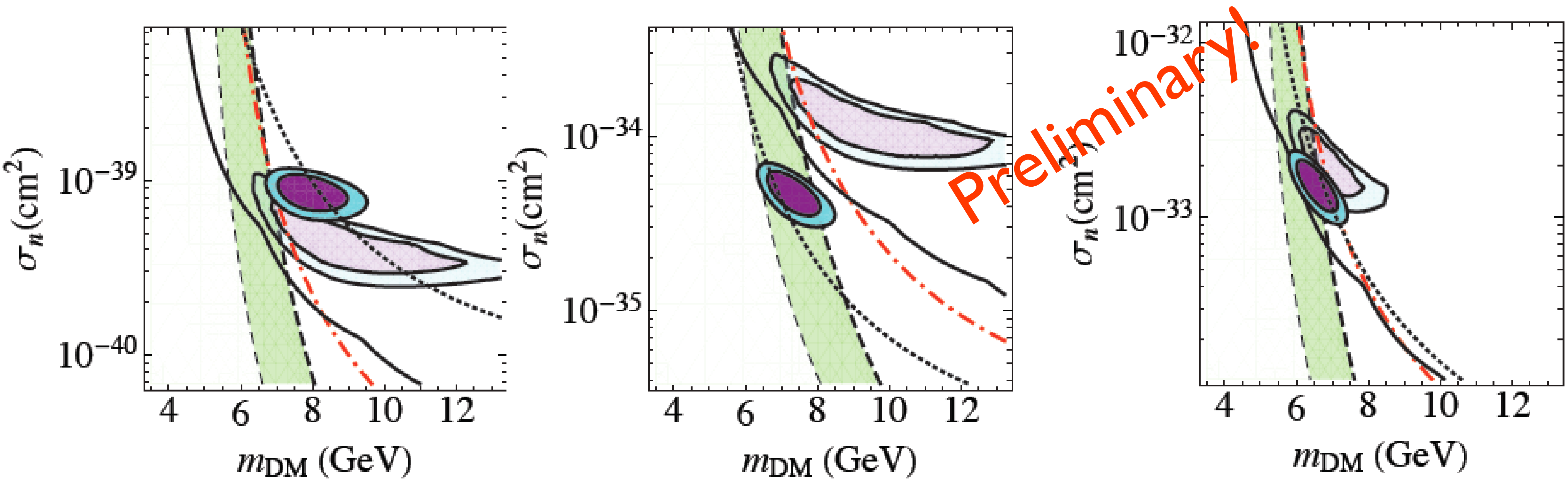



$$\mu_D \sim \frac{1}{\alpha_D m_\chi}$$

Dipole operator $\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu}/\Lambda$ is lowest dim'l gauge invariant allowed

# New CDMS results

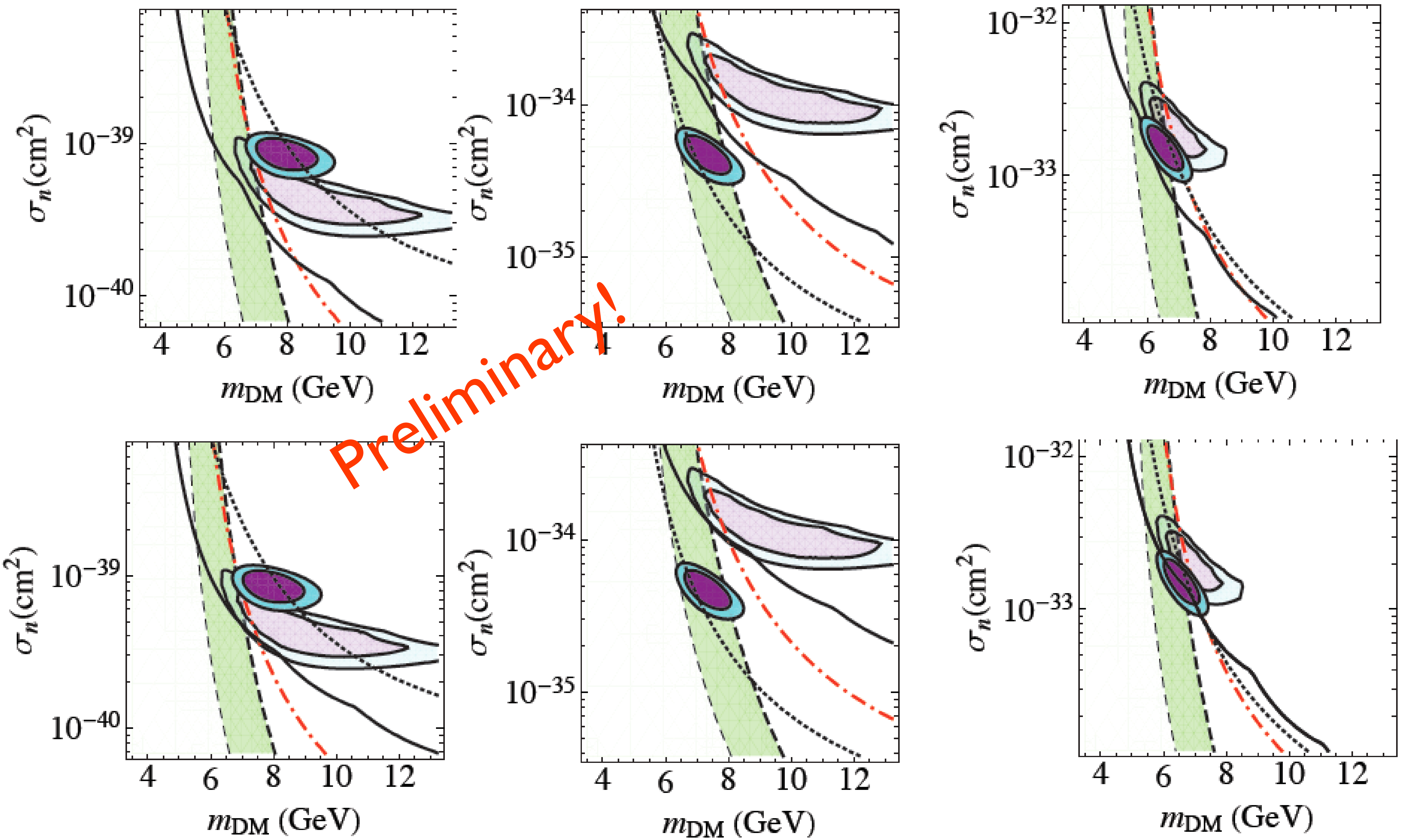



Also problematic: XENON10 S2 analysis

# New CDMS results

## 20% Energy shift has a significant effect



# Future: General Direct Detection EFT

- Constraints are typically calculated in a few simple models.
- Experiments are often said to disagree, but we've seen that more general models often change this.

$$
\begin{aligned}
V_{\text{eff}} &= V_{\text{eff}}^{\text{SI}} + V_{\text{eff}}^{\text{SD}} \\
V_{\text{eff}}^{\text{SI}} &= h_1 \delta^3(\vec{r}) - h_2 \vec{s}_\chi \cdot \vec{\nabla} \delta^3(\vec{r}) \\
&+ l_1 \frac{1}{4\pi r} + l_2 \frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3} \,, \\
V_{\text{eff}}^{\text{SD}} &= h_1' \vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r}) - h_2' \vec{s}_N \cdot \vec{\nabla} \delta^3(\vec{r}) \\
&+ l_1' \frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r} + l_2' \frac{\vec{s}_N \cdot \vec{r}}{4\pi r^3} \,,
\end{aligned}
$$

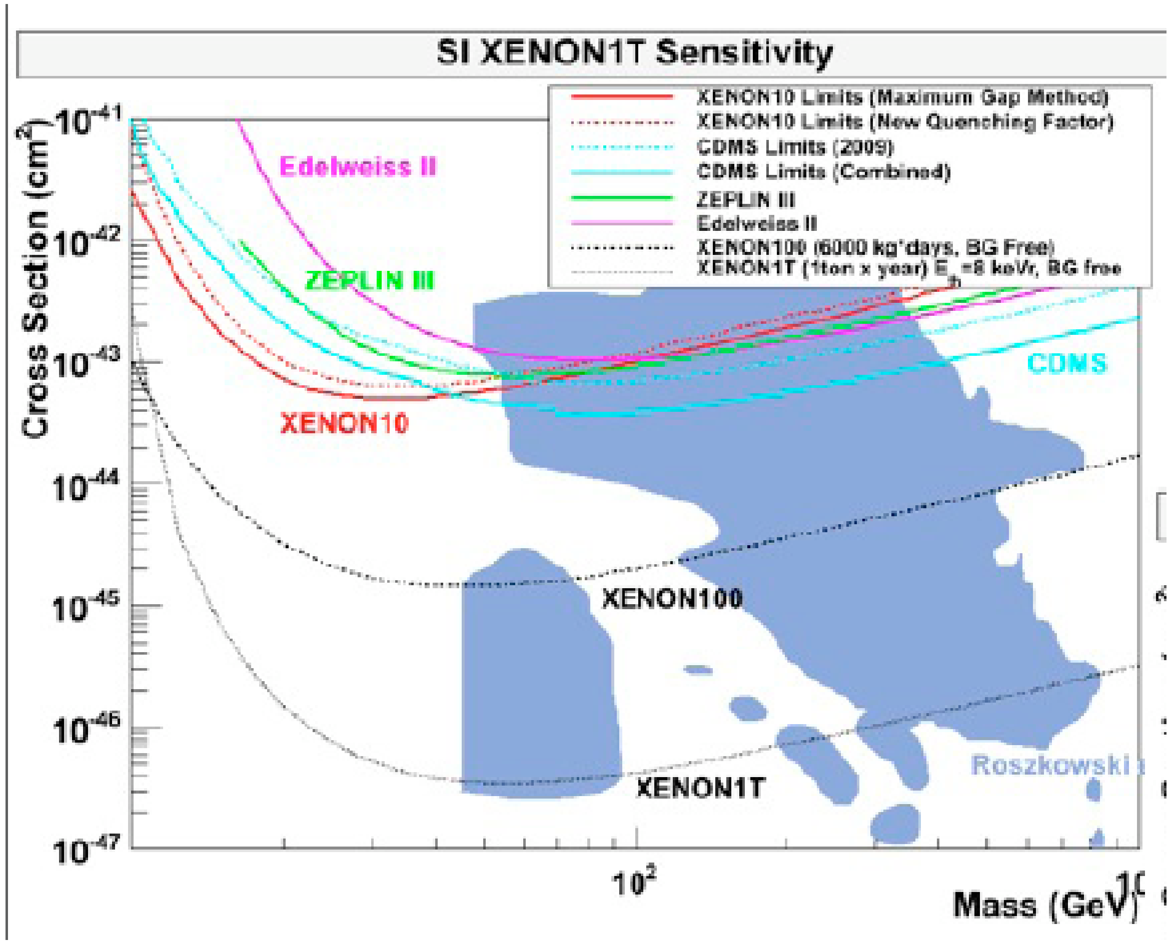
Fan et al:
Non-relativistic effective potential

# Future: General Direct Detection EFT

- Look at constraints in all possible directions in parameter space. For instance, dark magnetic dipole interaction was a combination of multiple terms.

$$
\begin{aligned}
V_{\rm eff} &= V_{\rm eff}^{\rm SI} + V_{\rm eff}^{\rm SD} \\
V_{\rm eff}^{\rm SI} &= h_1 \delta^3(\vec{r}) - h_2 \vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r}) \\
&\quad + l_1 \frac{1}{4\pi r} + l_2 \frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3} \ , \\
V_{\rm eff}^{\rm SD} &= h_1' \vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r}) - h_2' \vec{s}_N \cdot \vec{\nabla}\delta^3(\vec{r}) \\
&\quad + l_1' \frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r} + l_2' \frac{\vec{s}_N \cdot \vec{r}}{4\pi r^3} \ ,
\end{aligned}
$$

# Future looks exciting:




Aprile, Wonder conference

XENON1T, Super-CDMS

$$\sigma \sim 10^{-47}\mathrm{cm}^2 = 10\ \underline{\mathrm{yocto}}\ \mathrm{bn}$$

# Conclusion

- We are seeing rapid improvement in direct detection sensitivity
- DAMA, CoGeNT are potential signals of dark matter - worth considering alternative explanations
- Important to take into account all sources of uncertainty when making constraints
- Many models differ from standard WIMP scenario, worth trying to be model-independent.
- Exciting time for direct detection.